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INVESTIGATION OF THERMAL BEHAVIOR OF THE SELECTED LATENT HEAT STORAGE MATERIALS FOR THE TEMPERATURE RANGE OF 40-80^{O}C OF SOLAR HEATING APPLICATIONS

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ABSTRACT

The purpose of a latent heat storage system with the phase change material (PCM) is gaining significance for the storage of thermal energy due to the huge availability of solar radiation. In this study six kinds of materials are chosen from the points of view of high latent heat of fusion, high specific heat, non toxic, and low cost. These are four organic materials, namely; paraffin wax (58-60^{o}C), lauric acid, palmitic acid, Myristic acid, stearic acid, and one salt hydrate material such as sodium acetate trihydrate. An important aspect is to study a possible influence of the sample size on its thermal behavior. Hence, heating and cooling experiments have been performed to investigate the melting and freezing characteristics and effect of super cooling on the selected materials.

KEY WORDS: Phase Change Material (PCM); Super Cooling; Thermal Performance & Solar Heating Applications

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Original Article

1. INTRODUCTION

The availability of solar energy is more, which can be converted into heat energy with the support suitable technology. This technology is widely used in most of the applications like water heating, air heating, cooking applications, space heating, and industrial process heating. However, this solar energy is available only during the day. Hence, the demand for heat is at night and at the other times when there is little or no sunlight. Major problem exists since solar energy has intermittent nature. To overwhelming this problem with storage of heat either sensible heat or latent heat.

Sensible heat is the most commonly used method to store the heat. This heat is used to store the thermal energy whereby it varies the temperature of the storage material. Sensible heat is referred as the conventional storage. Typical examples of conventional storage mediums are water and rock [1]. Alternatively, another form of the thermal energy storage is latent heat, which makes use of energy stored when a substance changes from one phase to another by either melting or solidifying. In the latter, it has ability to provide latent heat that is able to store or release heat at constant phase transition temperatures when they undergo phase change. Therefore, the storage media is inferred as phase change material.

Normally, a phase change material absorbs or release energy when it undergoes phase change typically either solid to liquid or liquid to solid depends on particular applications. In case of cold temperature applications, phase change material absorbs energy during liquid to solid phase while release energy during solid to liquid phase. Whereas,

hot temperature application phase change material absorbs energy during solid to liquid phase while release energy during liquid to solid phase.

Socaciu [2] explained phase change diagram of the phase change materials. In that analysis Socaciu [2] mentioned that PCM's changes its phase such as solid- liquid, and liquid – vapour. Liquid to vapour involves absorption of heat during phase change which enables heat to be stored in a larger volume. Thus, a very large containment volume is required during the phase change process. In case of solid to liquid phase change is particularly attractive because it shows a very little volume change during the phase change process. Thus, it enables heat to be stored in a smaller volume. Solid to liquid type is most promising due to an isothermal nature of heat absorption and release during phase change which is most suitable candidate material for practical thermal energy storage applications.

In this study, phase change material is treated as a latent heat storage material. These latent heat storage materials are classified as organic, inorganic, and eutectic. Organic latent heat storage materials consist of paraffin's, and fatty acids. Inorganic latent heat storage materials consist of salt hydrates. Eutectic latent heat storage materials consist of both organic and inorganic materials.

In the open literatures, the common requirements are illustrated to select a latent heat storage material [1-3]. They are such as melting temperature, latent heat, specific heat at solid state and specific heat at liquid state, enthalpy – temperature relation, melting - freezing characteristics, effect of super cooling are the important properties for effective selection of phase change material. Out of all these properties of latent heat storage material the major importance gives to this material because of it has a severe super cooling behavior. Super cooling is a state where liquids do not solidify even below their normal freezing point of the substance. Typical example of super cooling behavior is observed in clouds at high altitude are containing tiny droplets of water below their freezing point. The sub cooling or super cooling effect the temperature has to be reached below the melting temperature of a material until it solidify and release heat during the cooling process of a latent heat storage material. If the latent heat storage material has severe sub cooling then the material temperature does not reach the melting temperature of the latent heat storage material during cooling process. Therefore, the phase change material will not solidify at all. Thus, it will store sensible heat only. Hence, it should always maintain less sub cooling or super cooling behavior. When the latent heat storage material is allowed to solidify, the actual solidification process does not initiate at its true phase transition temperature but few degrees lower than that. The temperature difference between true and actual melting point temperature represents the degree of super cooling. A phase change material is having a relatively small degree of super cooling, which is also a significant negative effect on heat release rate as a function of time which leads to reduce the efficiency of the storage system.

In order to measure the super cooling behavior of any latent heat storage material there are different methods used. The common methods are differential scanning calorimetry (DSC), differential thermal analysis (DTA), T-history method, and twin bath method. All the methods are suitable to measure the properties such as melting and freezing point, phase change latent heat and degree of super cooling. DSC and DTA give the accurate data and fast rate of response. Both methods can be used widest temperature test range and also it can be used to test the latent heat storage material properties. But, DSC fails to provide full information on the degree of super cooling and the freezing point of the substance due to the small quantity of sample is used. From DSC test it is also observed that the small quantity uses in the DSC pan may be maximized the tendency of super cooling behavior [4]. In general, super cooling phenomenon and nature of melting depends on the quantity of the latent heat storage material. It may vary substantially with a change of sample mass from milligrams to kilograms. Although the super cooling

behavior of the latent heat storage material can measure through other thermal analysis methods, they do not give reliable information about the bulk latent heat storage material behavior for practical large scale applications. In other thermal analysis methods like DTA is used very few milligrams of sample (approximately 1-50mg) [5]. Amongst various limitations which are associated with DTA method, few of them, including, poor sensitivity and accuracy and quantitative analysis are difficult to measure to get accurate data. Yinping et al. [6] reviewed these methods and observed their limitations such as small samples, complex and expensive equipment. Moreover; these methods are more accurate, but cannot observe visually phase change behavior. In view of disadvantages of the above methods they proposed T-history method, by this method; it can test the several thermal parameters including thermal conductivity, thermal diffusivity, and specific heat capacity, phase change temperature range, and phase change latent heat. Later studies that are modified by Marin et al. [7]. They developed evaluation procedure to determine the specific heat and enthalpy as function of temperature based on the same experimental procedure as followed by the yinping et al. [6]. It has some common errors which will occur in the T- history method, if the experimenter not completely breaks the component. However, these methods lack the possibility to measure bulk material sample amongst other drawbacks. Another method is a twin bath method was developed by demirel and paksoy [8]. Further, Paksoy [9] also studied thermal properties of heat storage materials using twin bath method. They conducted heating and cooling experiments on various materials such as paraffin, high density polyethylene, zinc nitrate tetrahydrate, ethylene glycol. The obtained results show that super cooling tendency is detected in the zinc nitrate tetra hydrate. In addition, that heat storage capacity, which includes sensible heat and latent heat is also possible to measure by using a twin bath method. Twin bath method has some attractive features such as apparatus are simple, and accuracy satisfies the engineering requirements. The operating test temperature range of twin bath method is 0-200^{o}C. The sample quantity is used in this method is very large compared to other methods. The main drawback is an uneven heating tendency occurs in the samples during the heating process and hence it leads to measurement error. Abat [10] reviewed various group of latent heat storage materials for low temperature solar heating and cooling applications in the temperature range of 0-120^{o}C and investigated melting and freezing characteristics of few phase change materials. He conducted experiments on two different kinds of apparatus such as glass test tube apparatus and glass container apparatus. Glass container apparatus reduces the amount of super cooling and recommended that the large glass surface helps in improving the nucleation conditions in the melt and the shallow bed assisted eliminating phase segregation effects in the molten material. They recommended that these two apparatus are suitable to investigate melting and freezing characteristics for large scale applications. The same experimental setup has been used here for estimation of sub cooling or super cooling of selected phase change materials.

In the initial study six kinds of latent heat storage materials such as palmitic acid, myristic acid, stearic acid, lauric acid, sodium acetate trihydrate, and paraffin wax are chosen based on high latent heat of fusion and high specific heat, low cost, non toxic and the desired selected temperature range (40-80^{o}C). It is observed that the selected materials and their properties are inconsistent due to its purity. Hence, in the initial study most important, prominent properties such as melting point, latent heat of fusion, the specific heat at solid and at liquid state are determined through DSC and clearly explained in Ref. [4]. In the present work experimental investigation of the melting - freezing characteristics, effect of super cooling of phase change material is carried out using glass tube apparatus. These properties are very important for exploration of heat storage potential of a phase change material. The above characteristics that belong to selection of appropriate phase change material and make them recognizable to give the reliable data for efficient and successful design of the storage system for a particular application.

2. EXPERIMENTAL METHODOLOGY

2.1 Selected Materials and their Specifications

In the present work the following latent heat storage materials, namely, stearic acid, palmitic acid, lauric acid, Myristic acid, paraffin wax and sodium acetate trihydrate have been selected and experiments are performed. The list of selected latent heat storage materials and their specifications are provided in Table 1.

Table 1: Specifications of Selected Heat Storage Materials

Name	Molecular Formula/Type	Purity (%)	Make
Paraffin wax	$C_nH_{2n+2,}$ n>20 Organic	-	SD Fine Chem Ltd
Sodium acetate trihydrate	$C_2H_3NaO_2.3H_2O$ Inorganic	99	SD Fine Chem Ltd
Myristic acid	$C_{14}H_{28}O_2$ Organic	90	SISCO Research laboratories Pvt. Ltd
Palmitic acid	$C_{16}H_{32}O_2$ Organic	99	SD Fine Chem Ltd
Stearic acid	$C_{18}H_{36}O_2$ Organic	90	SD Fine Chem Ltd
Lauric acid	$C_{12}H_{24}O_2$ Organic	99	SD Fine Chem Ltd

Heating and cooling experiments have been performed on a glass tube apparatus to investigate the melting and freezing characteristics and degree of super cooling of the selected latent heat storage materials. The geometry of the glass tube apparatus is selected based on a lumped model approach that satisfies the condition i.e, is biot number is less than 0.1. Figure 1 represents the experimental setup used for estimation of sub or super cooling. The main components of the experimental setup are the constant temperature water bath, glass tube, phase change material, data logger, *K*-type thermocouples, rubber cork stopper and holding stand. Calibrated *K*-type thermocouple is used to study the performance of the thermostatic water bath at various temperatures. The *K*- Type thermocouples are calibrated at 0^oC of ice. The glass tube is filled with 100grams of phase change material which is at solid state. Then the glass tube is closed with a rubber cork stopper. A hole is provided on the rubber cork stopper for a provision to insert *K*-type thermocouple sensor wire through it. One *K*- type thermocouple sensor wire is placed at the center of the phase change material in the glass tube. Another thermocouple sensor wire is in a water bath near to the glass tube. Water bath set at a temperature of 80^oC, the water is allowed to get heated up to the required temperature, and then the glass tube is immersed into the water bath. The glass tube is supported with the help of fixed stand to hold in vertical position. The two thermocouple sensor wires connect to the data logger. The data logger is an intelligent microcontroller based data acquisition system. This system was designed by Ambetronics Engineers Private Limited. This system consists of multiple data scanner model TC800D and analog to digital converter. It is capable of storing 5000 readings of all 8 channels. This system is provided with fixed input connections for all thermocouples, and optional serial ports. Flexibility is available to connect cables (RS-232 / RS-485) to analog to digital converter, and personal computer. The data which are acquired from the input and it is transmitted to analog to digital converter. It converts the data into digital form in which it is monitoring in the personal computer. The phase change material reaches to the steady state temperature in which it is monitoring continuously for a few minutes, then immediately the glass tube apparatus are placed into the cold water bath. The data is monitoring in the personal computer then the acquired date is used to plot heating curves and cooling curves against temperature vs time. During

the experiments it ensures that the following aspects. The uneven heating of temperature distribution in the water bath is avoided. The temperature readings are stored in the data logger software at every one second interval of time. The data is stored and it is reaching to the storage capability of the data logger then the stored data is retrieved through the data logger software and plotted graphs against temperature vs time. It is also taken care about the glass tube position in the thermostatic water bath and cold water bath. It is also ensured that the thermocouple sensor wire location should be fixed position at heating and cooling experiments. The rubber cork stopper is fixed to the glass tube to avoid passing environmental agent.

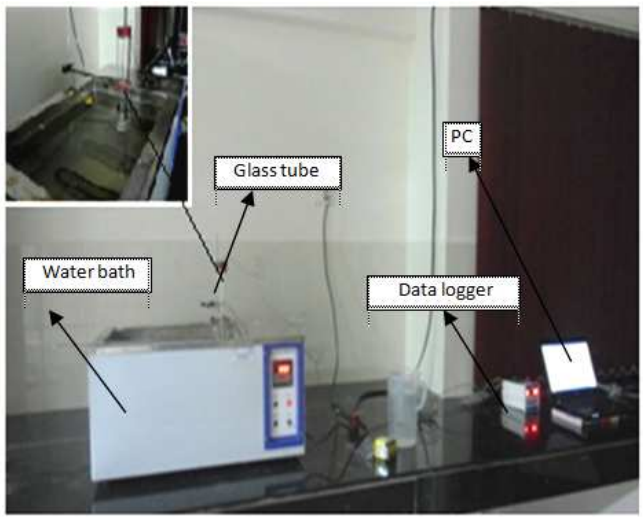

Figure 1: Experimental Setup for Estimation of Temperature Versus Time Variation of Selected Phase Change Materials

3. RESULTS AND DISCUSSIONS

From the experimental setup the experimentation is carried out with different selected phase change materials, temperature values are recorded at different fractions of time. The variation of temperature versus time is plotted and is described in the subsequent subsections.

3.1 Heating Curve of Lauric Acid

Figure 2 represents heating curve of lauric acid. During the heating process of lauric acid it undergoes a phase transition at a constant temperature of 46°C upto 153 seconds. It is found from the graph during heating process the sensible heating at solid state takes place by gradual increase in temperature of lauric acid from initial temperature 24°C to 46°C up to 153 seconds, and then the temperature is maintained at a constant temperature of 46°C for 122 seconds due to latent heat storage. The temperature then increases to the heat transfer fluid temperature (80°C) in 689 seconds. The total melting time is 964 seconds (approximately 16 minutes) for heating at 80°C. From the graph it can be seen that phase transition starts and completes at very less time and also at a heat transfer fluid temperature of 80°C.

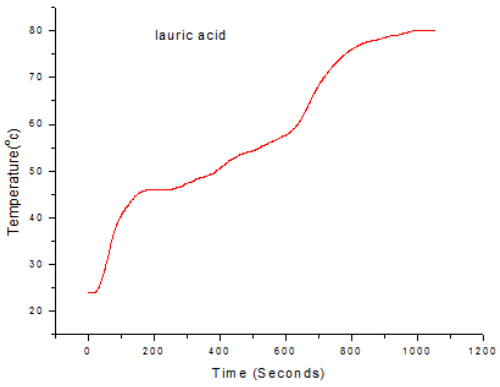

Figure 2: Heating Curve of Lauric Acid

3.2 Heating Curve of Paraffin Wax

Figure 3 shows a heating curve of paraffin wax. During the heating process it undergoes a phase transition at a constant temperature of 53°C. It is found from the graph during heating process the sensible heating at solid state takes place by gradual increase in temperature of paraffin wax from initial temperature 24°C to 53°C up to 79 seconds, and then the temperature is maintained at a constant temperature of 53°C for 780 seconds due to latent heat storage. The temperature then increases to the heat transfer fluid temperature (80°C) in 1150 seconds. The total melting time is 2009 seconds (approximately 33 minutes) for heating at 80°C. From the graph it can be seen that phase transition starts and completes at longer duration of time compared to other selected phase change materials and also the material exhibits constant melting temperature during phase transition.

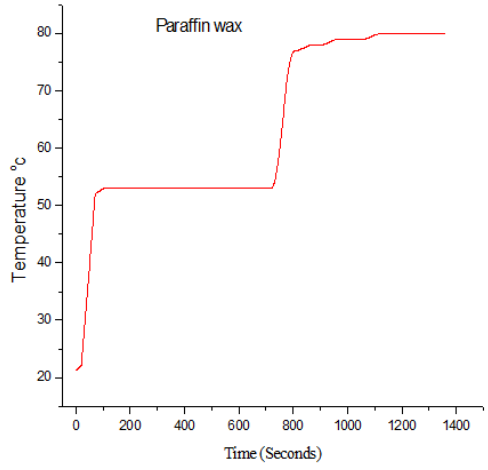

Figure 3: Heating Curve of Paraffin wax

3.3 Heating Curves of Stearic Acid

Figure 4 expresses the heating curve of stearic acid. From the Figure 4 it is observed that the material melts constantly at a temperature of 53°C during the heating process. During a heating process the material changes its phase from solid to liquid and it starts at a temperature of 24°C to 53°C up to 99 seconds and then the temperature remains constant 490 seconds at 53°C. The manufacturer provided a temperature range of this material is 53 to 59°C. From this graph it is evident that the phase transition temperature of stearic acid is 53°C. Finally, it reaches to steady state temperature in 817 seconds.

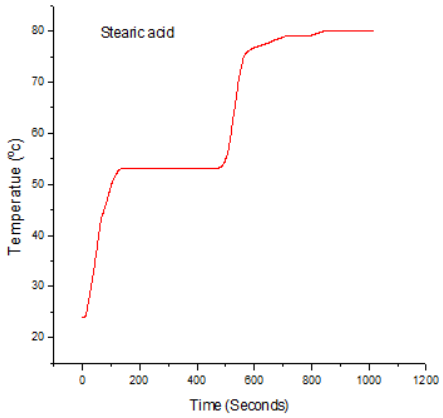

Figure 4: Heating Curve of Stearic Acid

3.4 Heating Curve of Myristic Acid

The temperature variation with time during the heating process of Myristic acid is shown in Figure 5. The graph shows phase transition temperature is at 51°C. Melting starts at a temperature of 24°C to 51°C up to 300seconds and then the temperature remains constant in the remaining 73 seconds at 51°C finally reaches to the temperature of 80°C up to 2570 seconds.

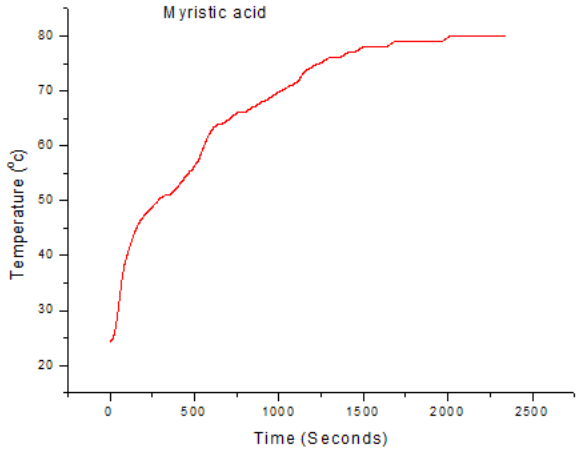

Figure 5: Heating Curve of Myristic Acid

3.5 Heating Curve of Palmitic Acid

Figure 6 shows the temperature variation with time during the heating process of palmitic acid. It starts at a temperature of 24°C to 61°C in 570seconds and maintains the same temperature for a period of 252 seconds at 61°C in which phase transition takes place. Then the behavior is reached to steady state at a temperature of 80°C in 1600 seconds as shown in Figure 6.

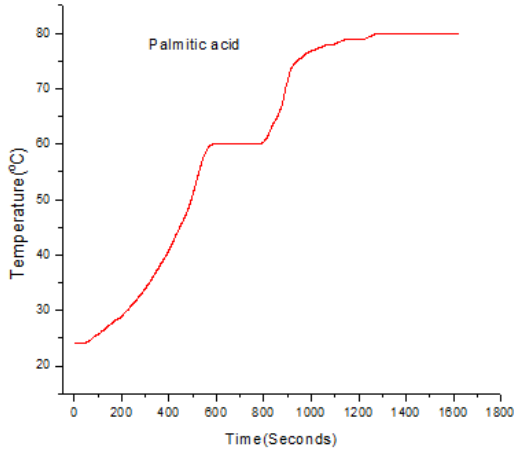

Figure 6: Heating Curve of Palmitic Acid

3.6 Heating Curve of Sodium Acetate Trihydrate

Figure 7 represents a heating curve of sodium acetate trihydrate. During the heating process it undergoes a phase transition at a constant temperature of 56°C. It is found from the graph during heating process the sensible heating at solid state takes place by gradual increase in temperature of sodium acetate trihydrate from initial temperature 24°C to 56°C up to 371 seconds, and then the temperature is maintained at a constant temperature of 56°C for 1826 seconds due to latent heat storage. The temperature then increases to the heat transfer fluid temperature (80°C) in 569 seconds. The total melting time is 2766 seconds (approximately 46 minutes) for heating at 80°C. From the graph it can be seen that phase transition starts and completes at longer duration of time and also the material exhibits constant melting temperature during phase transition.

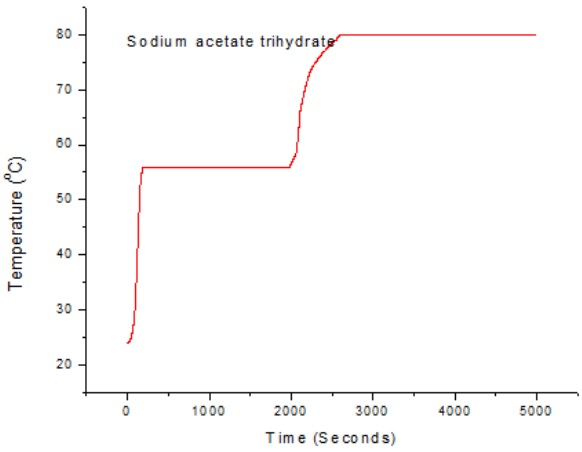

Figure 7: Heating Curve of Sodium Acetate Trihydrate

3.7 Colling Curve of Paraffin Wax

Figure 8 shows a cooling curve of paraffin wax. During the cooling process it undergoes a phase transition at a constant temperature of 53°C. It is found from the graph during cooling process the sensible heating at liquid state takes place by a gradual decrease in temperature of paraffin wax from initial temperature 80°C to 53°C up to 101 seconds, and then the temperature is maintained at a constant temperature of 53°C for 649 seconds due to latent heat storage. The temperature then decreases to the heat transfer fluid temperature (24°C) in 1450 seconds. The total solidification time is 2200 seconds

(approximately 36 minutes) for cooling at 24°C. From the graph it can be seen that phase transition starts and completes at very less time.

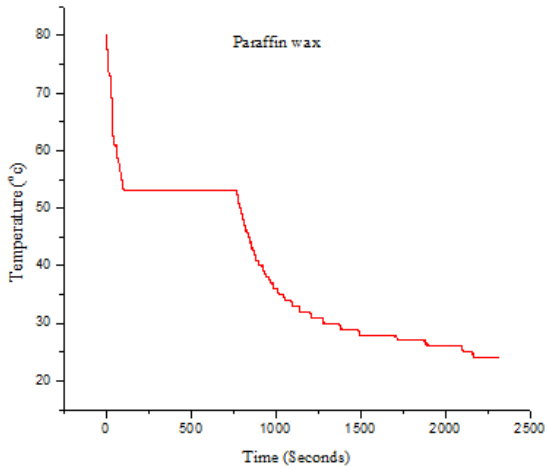

Figure 8: Colling Curve of Paraffin Wax

3.8 Colling Curve of Lauric Acid

The variation of temperature versus time of lauric acid is shown in Figure 9. Here the phase transition takes place at a constant temperature of 46°C. It is found from the graph during cooling process the sensible heating at liquid state takes place by a gradual decrease in temperature of lauric acid from initial temperature 80°C to 46°C up to 25 seconds, and then maintains the temperature at a constant temperature of 46°C for 180 seconds due to latent heat storage. The temperature then decreases to the heat transfer fluid temperature (24°C) in 240 seconds. The total solidification time is 445 seconds (approximately 7 minutes) for cooling at 24°C. From the graph it can be seen that phase transition starts and completes at very less time and also the material exhibits melting temperature, which is good agreement with the manufacturer provided data.

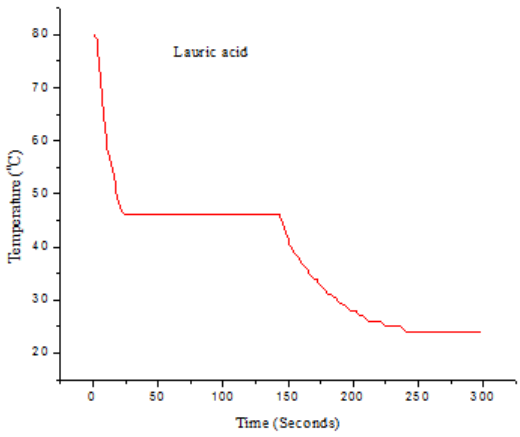

Figure 9: Colling Curve of Lauric Acid

3.9 Colling Curve of Palmitic Acid

Figure 10 represents a cooling curve of palmitic acid. During the heating process it undergoes a phase transition at a constant temperature of 63°C. It is found from the graph during cooling process the sensible heating at solid state takes place by a gradual decrease in temperature of palmitic acid from initial temperature 80°C to 63°C up to 107 seconds, and then the

temperature is maintained at a constant temperature of 63°C for 82 seconds due to latent heat storage. The temperature then decreases to the heat transfer fluid temperature (24°C) in 2440 seconds. The total solidification time is 2629 seconds (approximately 43 minutes) for cooling at 24°C.

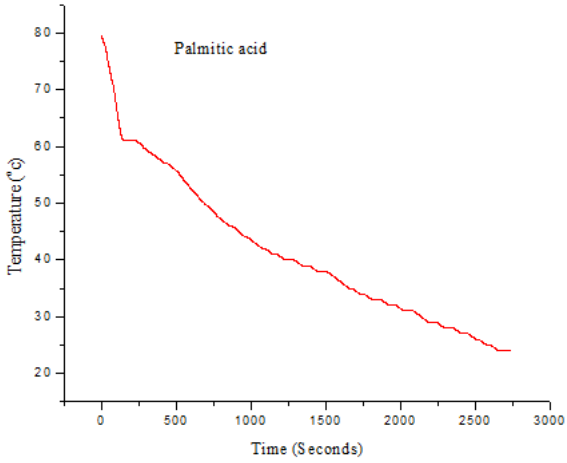

Figure 10: Colling Curve of Palmitic Acid

3.10 Colling Curve of Stesaric Acid

Figure 11 represents a cooling curve of stearic acid. During the cooling process it undergoes a phase transition at a constant temperature of 53°C. It is found from the graph during cooling process the sensible heating at liquid state takes place by a gradual decrease in temperature of stearic acid from initial temperature 80°C to 53°C up to 465 seconds, and then the temperature is maintained at a constant temperature of 53°C for 113 seconds due to latent heat storage. The temperature then decreases to the heat transfer fluid temperature (24°C) in 3579 seconds. The total solidification time is 4157 seconds (approximately 69 minutes) for cooling at 24°C.

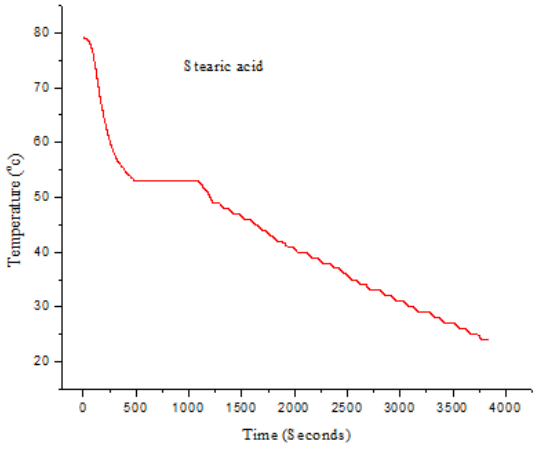

Figure 11: Colling Curve of Stearic Acid

3.11 Colling Curve of Myristic Acid

Figure 12 represents a cooling curve of Myristic acid. During the cooling process it undergoes a phase transition at a constant temperature of 53°C. It is found from the graph during cooling process the sensible heating at liquid state takes place

by a gradual decrease in temperature of Myristic acid from initial temperature 80°C to 53°C up to 123 seconds, and then the temperature is maintained at a constant temperature of 53°C for 78 seconds due to latent heat storage. The temperature then decreases to the heat transfer fluid temperature (24°C) in 2336 seconds. The total solidification time is 2537 seconds (approximately 42 minutes) for cooling at 24°C.

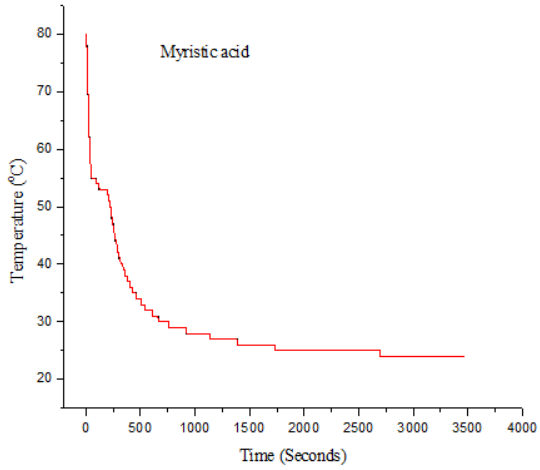

Figure 12: Colling Curve of Myristic Acid

3.12 Cooling Curve of Sodium Acetate Trihydrate

Figure 13 represents a cooling curve of sodium acetate trihydrate. During the cooling process it undergoes a phase transition at a constant temperature of 56°C. It is found from the graph during cooling process the sensible heating at liquid state takes place by a gradual decrease in temperature of sodium acetate trihydrate from initial temperature 80°C to 26°C up to 1639 seconds, then a sudden rise of temperature and reaches to phase transition temperature 56°C up to 80 seconds then a gradual decrease of temperature and reaches to heat transfer fluid temperature at 24°C up to 2103 seconds.

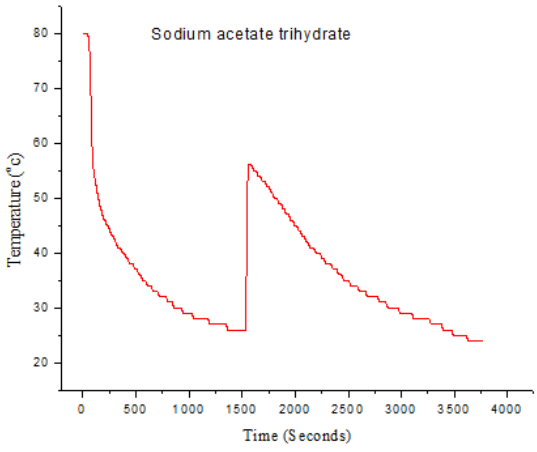

Figure 13: Colling Curve of Sodium Acetate Trihydrate

4. CONCLUSIONS

From this study it is observed that sodium acetate trihydrate gives the highest amount of heat storage capacity compared to other selected latent heat storage materials. Amongst the latent heat storage materials, sodium acetate trihydrate

exhibit the super cooling behavior. Another aspect, it is observed that the heat exchange rate is more due to high thermal conductivity compared to other materials. From this study it is also observed that paraffin wax, stearic acid, and lauric acid are shown low latent heat of fusion compared to sodium acetate trihydrate. During the heating process, the melting time is shown very less to reach phase transition temperature of the phase change materials. Thus, these are suitable for short term thermal energy storage applications. Remaining materials such as palmitic acid and Myristic acid are shown high heat storage capacity and more time to reach phase transition temperature. Therefore, these two materials are suitable for long term thermal energy storage applications. This study is evident that the selected phase change materials have the capability to serve as thermal energy storage for solar heating applications. Based on this study it is observed that sodium acetate trihydrate material has detected super cooling behavior and other materials have not affected the super cooling. But this material has shown high enthalpy as compared to other material.

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